Simulation of Evapotranspiration of Applied Water II – SIMETAW II

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Introduction

The SIMETAW II computer application program was written using Microsoft C# for calculations and Oracle for data storage to provide a tool for estimating crop evapotranspiration (ET_c) and evapotranspiration of applied water (ET_{aw}), which is a seasonal estimate of the water needed to irrigate a crop assuming 100% irrigation efficiency. Crop evapotranspiration is computed as the product of reference evapotranspiration (ETo) and a crop coefficient (Kc) value, i.e. ETc = $ET_o \times K_c$, and ET_{aw} is equal to the seasonal evapotranspiration minus water supplied by stored soil moisture and by effective rainfall. The SIMETAW II application is specifically designed to estimate ET_{aw} within the Sacramento and San Joaquin Valleys (i.e. the Central Valley of California). It does not account for irrigation system efficiency or for leaching fractions needed to control salinity. SIMETAW II does include the contribution from rainfall and it has the ability to account for ground water seepage from the rivers and canals if it is possible to provide spatial information on the depth to water tables on the same 4×4 km grid spacing used to characterize soils in the Central Valley.

In the SIMETAW II project, huge soil and climate database were developed to spatially characterize ET_c and ET_{aw}. It is our understanding that DWR Information Technology (IT) has recently adopted the use of Oracle and C# for their software for DWR applications. Therefore, Oracle was used to store the daily climate data, i.e. maximum (T_x) and minimum (T_n) temperature and precipitation (Pcp), which were derived from monthly PRISM (USDA-NRCS) data that cover California on a 4×4 km grid spacing. Because the PRISM data are monthly and daily data are needed to determine ET_{aw}, daily NCDC climate station data, back to October 1921, were used with the PRISM data to estimate daily T_x, T_n, and Pcp. The daily climate data development is described later in this report.

A second database containing the soil water holding capacity, soil depth, and rooting depth information for all of California was also developed from the USDA-NRCS SSURGO database. The developed data base covers all of California on the same 4×4 km grid for all loca-

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tions that are included in the SSURGO database, which is most of California. There are a few locations, mainly outside of major agricultural regions, that did not have soil surveys in the SSURGO database.

A major goal of this project was to develop a computer application program to estimate daily soil water balances for surfaces within the Central Valley that account for evapotranspiration losses and water contributions from rainfall, seepage of ground water, and irrigation. The water balance model is similar to that used in the Simulation of ET of Applied Water (SIMETAW) application program, which was also developed as a cooperative effort between the University of California (UC) and the Department of Water Resources (DWR). Because there are thousands of soil and cropping pattern combinations (including differences in cropping seasons), it is impossible to account for all combination in the Central Valley. The biggest limitation is the lack of cropping pattern information from 1921 to the present. In recent years, however, the cropping information has dramatically improved and refinements are likely in the future.

Using mean soil characteristics and climate and ET_o information from the 4x4 km grid, SIMETAW II can estimate the mean soil characteristics and mean ET_o information by depletion study area (DSA). The main difference between the original SIMETAW model and SIMETAW II is that SIMETAW determines the daily water balance of individual fields of crops within a watershed region using historical or generated climate data and one set of ET_o estimates, whereas SIMETAW II uses batch files of soil and climate data to compute daily water balance based on historical or generated climate data for several land-use categories over the period of record by DSA. Thus, each DSA has its own unique records of evaporative demand and precipitation. Using SIMETAW II is like repeating SIMETAW 46 times to cover all DSAs in the Central Valley. In SIMETAW, the output data were archived in comma delimited “csv” files that were readable using Excel. SIMETAW II retrieves the data it needs from an Oracle database, computes DSA water balances for each of 17 surface categories in each of 46 DSAs and outputs the results to an Oracle database. The result is a huge savings in time and effort to obtain the best possible crop evapotranspiration and ET_{aw} information for the Central Valley.

Land Use by Depletion Study Areas

Central Valley historical land-use was archived for each of 46 DSAs for the water years 1922-2003, with the 1992 through 2003 data provided by the Bay Delta Office. The historical land-use data originated from the California Department of Food and Agriculture (CDFA) and DWR –

Topic: Crop Water Use SIMETAW II

Northern, Central, and San Joaquin District Offices and the Land and Water Use Staff in the Division of Planning and Local Assistance (DPLA). Surveys are conducted every five to seven years, and the data were interpolated between survey years. The results are adjusted annually based on Agricultural Commissioner Reports. Land-use data were developed by the DWR Division of Planning and Local Assistance (DPLA) for the California Water Plan Update (Bulletin 160).

The land-use distribution was archived in 46 separate comma delimited "csv" files corresponding to the DSAs. The files were named "DSA0nn.csv", where "nn" is a 2-digit DSA number. DSAs 49 and 60 have several subareas, so they have an additional letter following the 2-digit number to identify the subarea, e.g. 49a, 49b, 49c, 49d, 60a, 60b, 60c, 60d, 60e, 60f, 60g, and 60h. In each "csv" file, the number of acres was listed in 17 land-use categories (columns) for the 82 years (rows). A partial sample of the data in the file "DSA060h.csv" is shown in Table 1. In the data file, the first column identifies the water year and the second column identifies the type of water year. Years with the symbol 'C' or 'D' in the second column are critical (dry) water years and all other symbols are for non-critical water years. The remaining columns contain the areas (acres) for each of the 17 land-use categories. The 17 land-use categories are identified in row 1 of the files and the land-use categories are numbered in row 2. The 46 DSA land-use files are stored in a folder named "Historical" in the SIMETAW II analysis folder. Note that, in the historical files, there are smooth changes in the surface areas of the land-use categories over time. Land-use data were only available for 22 of the DSAs, but SIMETAW II was designed to use land-use data from all of the DSAs as data are made available.

Land-Use Categories

The SIMETAW II application uses 17 land-use categories. Each category includes one or more crops or other surfaces. The land-use categories and what they include vary depending on the source of the information (i.e. GIS survey, DICU model, or CU model). A sample of the land use for DSA 60H for water years 1922-1940 is shown in Table 1.

Table 1. Sample land-use data for DSA 60H from water years 1922-1940. Note that the actual "DSA060H.csv" data file contains data for water years 1922-2003. The land-use files are comma delimited. Row 1 contains the abbreviations of the 17 land-use categories (definition are in Table 2). The crop numbers are given in row 2. The year is provided in column 1 and the water year type is given in column 2. The figures in the table are the area planted in acres corresponding to the crop and year.

DATE	TYPE	UR	PA	AL	FI	SB	GR	RI	TR	TO	CO	OR	VI	SO	RV	NV	DGR	WS
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1922	AN	7231	4376	42223	23837	1233	0	381	15484	0	38277	6450	14290	0	0	499141	0	0
1923	BN	7422	4395	42426	23931	1233	0	381	15523	0	38522	6479	14358	0	0	498253	0	0
1924	C	7612	4420	42628	24048	1245	0	381	15600	0	38682	6516	14427	0	0	497364	0	0
1925	D	7802	4438	42831	24165	1245	0	389	15678	0	38866	6545	14496	0	0	496468	0	0
1926	D	7993	4463	43076	24297	1258	0	389	15755	0	39075	6581	14576	0	0	495460	0	0
1927	W	8183	4482	43279	24414	1258	0	389	15832	0	39271	6610	14645	0	0	494560	0	0
1928	AN	8183	4507	43481	24523	1270	0	389	15910	0	39456	6639	14713	0	0	493852	0	0
1929	C	8373	4526	43684	24640	1270	0	396	15987	0	39628	6676	14782	0	0	492961	0	0
1930	D	8564	4445	42903	24204	1245	0	389	15716	0	38928	6552	14519	0	0	495458	0	0
1931	C	8944	4369	42165	23783	1233	0	381	15445	0	38228	6443	14267	0	0	497665	0	0
1932	D	9325	4288	41385	23339	1208	0	373	15136	0	37552	6319	14003	0	0	499995	0	0
1933	C	9515	4207	40604	22903	1184	0	366	14865	0	36840	6203	13740	0	0	502496	0	0
1934	C	9896	4132	39866	22482	1159	0	358	14594	0	36165	6086	13488	0	0	504697	0	0
1935	BN	10276	4050	39085	22046	1134	0	351	14323	0	35452	5970	13225	0	0	507011	0	0
1936	BN	10657	3969	38305	21602	1122	0	343	14013	0	34752	5853	12961	0	0	509346	0	0
1937	BN	10847	3887	37524	21165	1097	0	335	13742	0	34052	5729	12698	0	0	511847	0	0
1938	W	11228	3812	36786	20745	1073	0	328	13471	0	33365	5620	12446	0	0	514049	0	0
1939	D	11608	3731	36005	20309	1048	0	328	13161	0	32665	5496	12183	0	0	516389	0	0
1940	AN	11799	3950	38102	21493	1110	0	343	13936	0	34556	5824	12893	0	0	508917	0	0

Table 2. Components of the 17 land-use categories for the GIS survey, DICU model, and CU model.

No.	Land-use Category	Symbol	GIS Survey	DICU Model	CU Model
1	Urban	UR	Urban, Commercial, Industrial, Landscape, Residential, Vacant, Semi-Agricultural	Urban	Urban
2	Pasture	PA	Pasture	Pasture	Pasture
3	Alfalfa	AL	Part of Pasture	Alfalfa, Non-Irrigated Pasture	Alfalfa
4	Field Crops	FI	Field, Safflower, Corn	Field, Safflower, Corn	Field
5	Sugar Beets	SB	Part of Field Crop	Sugar Beets	Sugar Beets
6	Grain	GR	Grain & Hay	Grain	Grain
7	Rice	RI	Rice	Rice	Rice
8	Truck	TR	Truck,	Truck	Truck
9	Tomato	TO	Part of Truck Crop	Tomato	Tomato
10	Cotton	CO	Cotton	Cotton	Cotton
11	Orchards	OR	Deciduous Fruits & Nuts	Orchards, Non-Irrigated Orchards	Orchards
12	Vineyards	VI	Vineyards	Vineyards, Non-Irrigated Vineyards	Vineyards
13	Citrus & Olive	SO	Subtropical (citrus) & Olives		
14	Native Riparian	RV	Riparian Vegetation	Riparian Vegetation	Riparian Vegetation
15	Native Vegetation	NV	Native Vegetation, Native Classes Unsegregated, Idle, Barren Wasteland	Native Vegetation	Native Vegetation
16	Non-Irrigated Grain	DG	Part of Grain and Hay	Non-Irrigated Grain	Non-Irrigated Grain
17	Water Surface	WS	Water Surface	Water Surface	Water Surface

Crop Percentages

Data on land-use was available for the 17 land-use categories by DSA for the 82 year study period, but, because surveys are infrequent, information on the individual crop (sub-category) areas within the land-use categories was mostly unavailable. To overcome this problem, the individual crop acreages, within each DSA, were estimated using the 2003 CDFA California Crop Report. Since DSAs often overlap two or more counties, a uniform crop distribution was assumed within each county, and the percentage of each county falling within a DSA was used to estimate the crop acreage that fell within a given county-DSA overlap. The sum of all county contributions to a DSA was computed to obtain the total acreage for each crop within each DSA.

Land-use categories that represent individual crops have seasonal crop coefficient (K_c) curves, but categories containing multiple crops or other surfaces do not have a single seasonal K_c curve. These multiple surface sub-categories, however, generally have one or two dominant surfaces, and therefore it was possible to determine a weighted mean seasonal K_c curve using the percentages of the entire land-use category corresponding to the sub-category crops and surfaces. Crop coefficient (K_c) and growth information by crop were used to determine the weighted mean K_c values. Weighted mean K_c values and growth dates were computed for each of the 17 surface categories using the percentage of the surface category acreage occupied by individual crops within a DSA using the 2003 Annual Crop Report from the California Department of Food and Agriculture. A comma delimited "csv" file containing the surface and soil information for each DSA was created. Weighted mean available water holding capacity (AW) and maximum soil depth (SD_x) were determined for each DSA and archived in '.csv' files (e.g. DSA003GA.csv for DSA 3.

Reference Evapotranspiration (ET_o)

Reference evapotranspiration (ET_o), an estimate of the evapotranspiration from a well-watered, improved pasture, is technically defined as the ET from a short 12 cm tall vegetation of large extent and not lacking for water. In practice, ET_o is approximately equal to the ET of a 12 cm tall, cool-season pasture grass. The SIMETAW II program uses ET_o and crop coefficients to estimate crop ET (ET_c) assuming no water or salinity stress. Documentation on how ET_o is calculated is provided in the SIMETAW section of this Bulletin.

Climate data

To estimate ET_o, SIMETAW II uses the Hargreaves-Samani (HS) equation (Appendix A) and daily maximum and minimum temperatures, on a 4×4 km grid spacing over the Central Valley, from the USDA PRISM climate database for the period of record. Calibration factors to convert from the HS estimates of ET_o to the standardized Penman-Monteith (PM) daily (24-hour) ET_o (Appendix A) were determined by comparing ETo calculated using the PM equation using daily solar radiation, maximum and minimum temperature, the mean dew point temperature, and mean wind speed with HS ET_o calculated from daily maximum and minimum temperature. The data for calculating PM ET_o came from CIMIS stations and the data for calculating HS ET_o came from nearby NCDC stations. The ET_o calculation methods are explained in Appendix A, and the procedure to develop conversion factors from HS to PM ET_o is explained below.

PRISM

PRISM is a data base that was developed by the USDA to spatially estimate climate variables from climate data and to account for elevation. The PRISM software generates gridded estimates of climatic parameters (e.g. precipitation and temperature). It uses a moving-window regression of climate values from nearby climate stations versus elevation or climatology for each grid cell. A spatial climate knowledge base weights data in the regression function according to their physiographic similarity to the target grid cell. PRISM accounts for spatial variations in climate due to: (1) elevation, (2) terrain orientation (rain shadows), (3) terrain profile (enhancement of precipitation), (4) moisture regime (exposure to moisture sources), (5) coastal proximity, (6) two layer atmosphere (inversion layer and free atmosphere), and (7) topographical position (susceptibility to cool air pooling). The monthly PRISM data were masked and then reprojected to obtain an equal area raster map for California on a 4×4 km grid for the period 1920 through 2007 for maximum temperature (T_x), minimum temperature (T_n), and significant precipitation (P_{cp}). Precipitation was considered significant if the precipitation was twice the mean daily HS ET_o rate.

Procedures used to estimate historical ET_o

The following steps were followed to estimate ET_o using the PRISM climate data.

1. PRISM CONUS (Continental US) climate data were input and reprojected to an equal area raster map for California to create monthly gridded climate data for California (4 km resolution).

2. The PRISM California climate data grids were converted to a DWR database input format.
3. A conversion factor to convert from the Hargreaves-Samani (HS) equation ET_o to the Penman-Monteith (PM) equation estimate of ET_o was determined using NCDC and available corresponding CIMIS data.
   - NCDC station data were used to compute HS ET_o and they were compared with neighboring CIMIS station PM ET_o to determine site specific correction factors for each CIMIS station location. Data were selected from the UC IPM site.
   - Spatial interpolation was accomplished using an ARC GIS to obtain a 4 km gridded raster map (cfhs).
4. Central Valley NCDC stations were used to develop a lookup table for neighboring stations.
5. NCDC climate data were prepared for the Postgres database by reformatting the NCDC data (QAQC) and calculating temperature deviation and the fractional precipitation time series data over 87 years.
6. Spatialization of NCDC climate data was accomplished using GRASS GIS by calculating 2 km gridded raster data sets for temperature deviation (DTx, DTn) and the fractional precipitation (DPcp).
7. CIMIS-GOES 2 km ETo and climate products were reprojected to 4 km resolution raster maps (R_s, T_x, T_n, U, and T_d). Note that Rs is solar radiation (MJ $m^{-2}d^{-1}$), U is the wind speed (m s^{-1}) and T_d is the dew point temperature (^oC).
8. Daily climate gridded rasters were calculated in GRASS GIS using the specialization in task (6) and monthly PRISM data (1): T_x, T_n, and Pcp.
9. Daily California climate grids were converted to a comma delimited database input format (*.csv).
10. Daily gridded rasters for extraterrestrial radiation (R_a), HS ETo were calculated using R_a, T_x, T_n, PM ETo (from the HS ETo and cfhs), and the number of significant rainy days (NRD). Note that daily R_a was calculated as a function of latitude and day of the year following Allen et al. (2005).
11. A monthly summary of NRD was derived.
12. The monthly NRD grids in combination PRISM California grids were converted to the database input format used by DWR.
13. The previous steps were iterated to insure data quality and to eliminate data problems.

14. A daily precipitation product from the NWS was identified for ongoing use (i.e. with CIMIS-GOES). CIMIS-GOES is a model to provide spatial estimates of ETo using CIMIS weather data and remote sensing from GOES. An explanation and example are provided on the DWR- CIMIS webpage.

***ET_o* Correction Factors**

NCDC stations were paired with neighboring CIMIS stations from the time when the CIMIS station came on-line. Corresponding data for the paired stations were selected from the UC IPM site (http://ipm.ucdavis.edu). The PM equation was used to calculate reference evapotranspiration (ET_o) using daily CIMIS data and the HS equation was used to calculate ET_o (ET_{HS}) using daily T_x and T_n data. The calculation methods for PM and HS are given in Appendix A. The correction factor (C_F) was calculated as:

$$C_F = \frac{ET_o}{ET_{HS}}$$

Spatial interpolation was completed using ARC GIS and a 4 km gridded raster map for C_F was produced (Fig. 2). The C_F values fell within 15% of 1.0.

The C_F values were archived for each 4×4 km grid area, and the grid areas were stored in files designated by the DSA number (e.g. DSA003GA.csv for DSA 3.

Soil Characterization

The available soil water holding capacity (AW) and maximum soil depth (SD_x) database was developed from the USDA-NRCAS Soil Survey Geographical Database (SSURGO Ver. 2.2), which covers California on a 4×4 km grid. There were a few locations, mainly outside of major agricultural regions, that did not have soil surveys in the SSURGO database. The AW was computed as the mean available soil water holding capacity over the SD_x for each soil within a 4×4 km grid area. The weighted mean AW was then calculated over all soils within the grid area and the results were archived by grid area. Note that the AW content is unitless (mm/mm). The AW and SD_x for each DSA were computed as the means over grid areas falling within the DSA. The values for AW and SD_x were archived by crop category for the 46 DSA files that contain crop and soil information

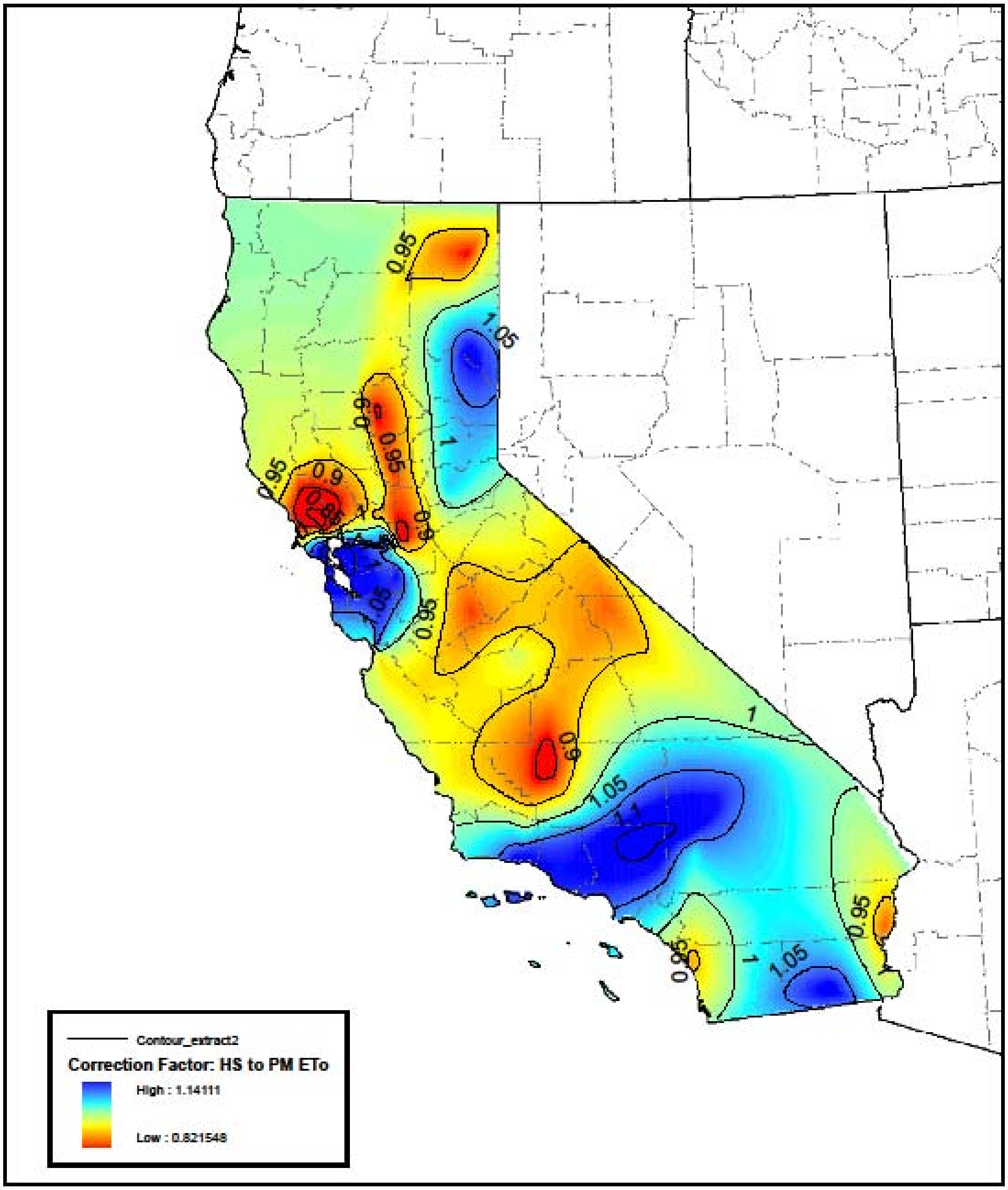

Figure 2. Correction factor (C_F) distribution for converting Hargreaves Samani ET_o (ET_{HS}) to Penman- Monteith ET_o for California. Note that $ET_o = HT_{HS} \times C_F$.

Rooting Depth and Plant Available Water

Maximum crop rooting depth (RD_x) information is archived in the "CropRef" worksheet in the Excel file "KcDSA.xls", which was used to determine weightings for crop coefficient curves and maximum rooting depths. The RD_x values for most individual crops were provided by the DWR Division of Planning and Local Assistance. Additional rooting depths were extracted from the UN Food and Agriculture Organization Irrigation and Drainage Paper 33 (Doorenbos and Kassam, 1979). All of the rooting depths were input into the "CropRef" worksheet of the "KcDSA.xls" file. The number of acres for each crop was entered by county in the columns CW through EG in the ACRES worksheet.

The percentage of each county that fell within a given DSA was visually estimated from the DSA and county overlay maps (Figs. 3 and 4). The county names and estimated percentages of the county falling within a given DSA were entered in row 4, columns E through AY. The appropriate percentages in row 4 were multiplied by the county crop acreages to determine the county crop acreage falling within each DSA. Then the total acreage within the DSA was determined by calculating the sum of the county acreages within a DSA. The acreages of individual crops were summed to determine the total acreage for each land-use category for all of the DSAs. The DSA individual crop acreages and land-use category acreages are given in the "ACRES" worksheet in columns E through CT. The "PERCENT" worksheet contains the percentages of each crop falling within each of the DSAs. Note that the land-use category percentage, which is the sum of the crop percentages within each category, is always equal to 100%.

The weighted maximum rooting depth (RD_x) for individual crops was calculated by finding the product of RD_x data from the "CropRef" worksheet and the corresponding percentage of the land-use category from the "PERCENTAGE" worksheet. The RD_x results were saved by crop in each of the 46worksheets "C3, C5, C10, etc." The weighted mean maximum rooting depth for each land-use category was determined by summing the products over all crops within each of the categories. The weighted mean RD_x results were saved by land-use category in the respective 46 DSA worksheets 3, 5, 10, 11, 12, 14, etc. in the "KcDSA.xls" spreadsheet. Then, each of the worksheets was saved as an individual crop and soil information "CSI" comma delimited csv files as: DSA003CSI.csv, DSA005CSI.csv, DSA010CSI.csv, DSA011CSI.csv, etc. These "CSI" files are read by the SIMETAW II program to determine the weighted crop coefficient curves and plant available water content for combinations of DSA and land-use category.

Note that there was no calculation of the RD_x when there was no acreage recorded for a particular DSA and land-use category combination and a value "0" was recorded for that DSA and land-use category in the "KcDSA.xls" spreadsheet. The "0" values were replaced with the RD_x values, for the same land-use category, from DETAW.

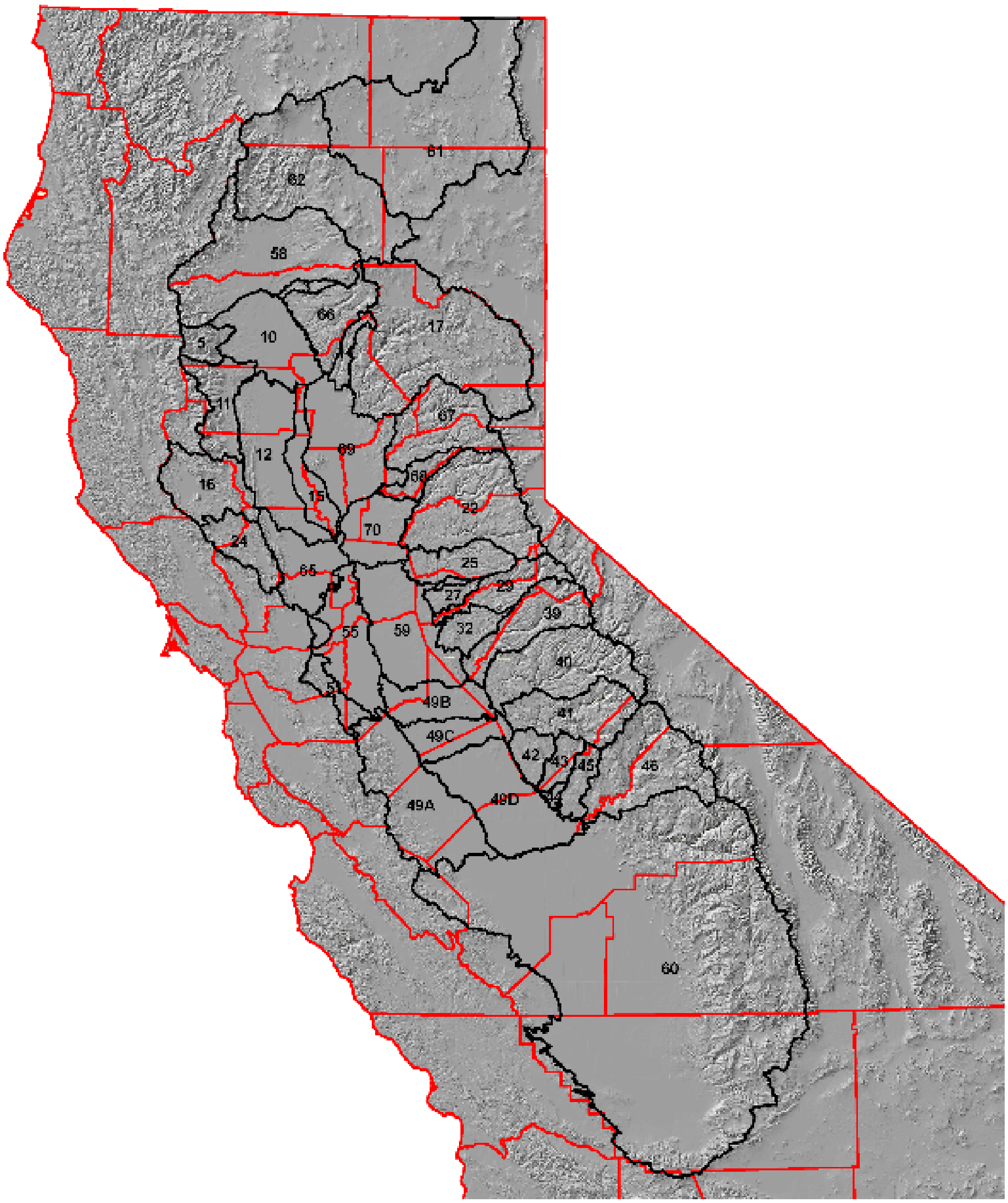

Figure 3. DSA and county map for the Central Valley

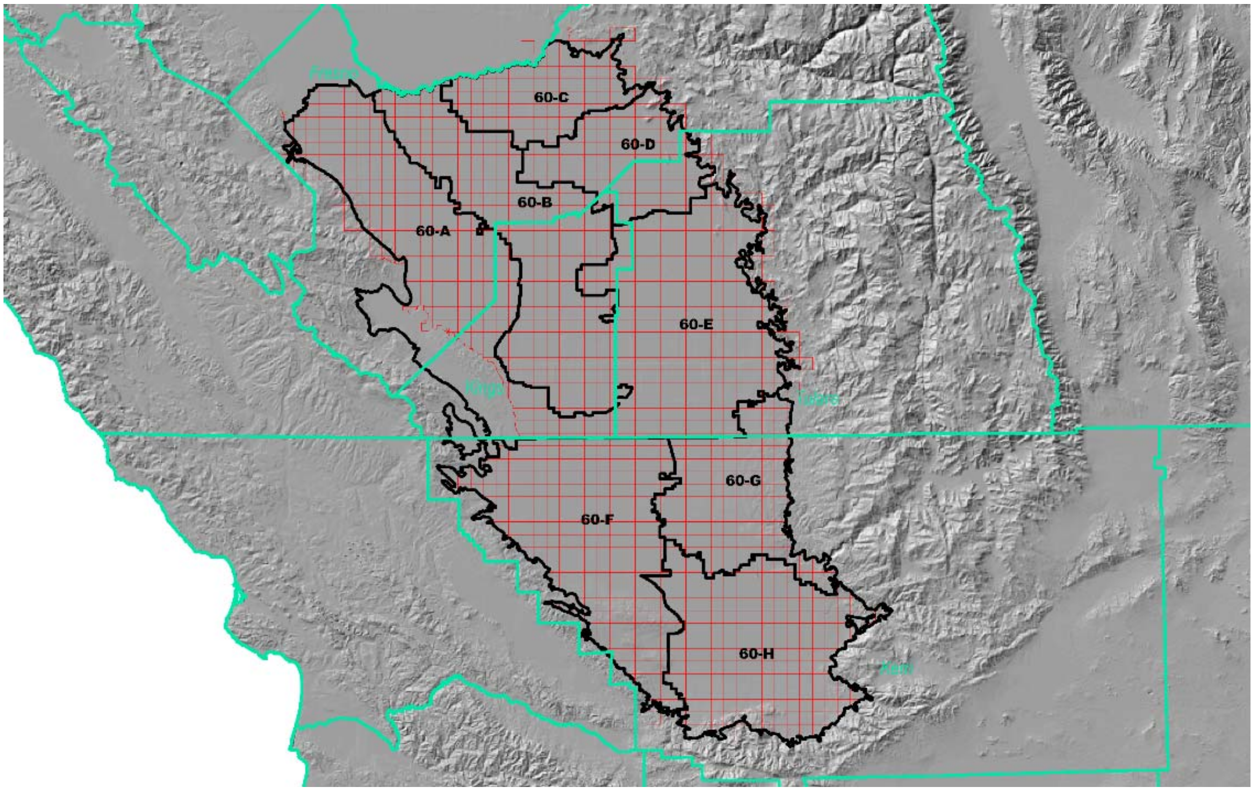

Figure 4. DSA and county map for DSA 60 sub-areas.

Crop Coefficient Curves

The basic concept of crop coefficient (K_c) factors is explained in SIMETAW section of this Bulletin. In SIMETAW II, seasonal K_c curves are used to estimate evapotranspiration for the 17 various land-use surfaces. The land-use categories include combinations of various surfaces that generally have similar characteristics. Most of the categories are associated with crop types, but a few categories do not included crops (e.g. riparian vegetation and urban landscape). Therefore, the use of “crop” with coefficient is strictly incorrect. While the K_c values are used to estimate the evapotranspiration rates of land-use categories in a similar manner as crop evapotranspiration, from this point forward, we will simply use the symbol K_c rather than the name “crop coefficient” for the factors that are multiplied by reference evapotranspiration (ET_o) to estimate the ET of a particular land-use category. We will use the symbol ET_c, which is commonly used for crop evapotranspiration, as the symbol for evapotranspiration by the land-use category. Therefore, the land-use category evapotranspiration rate on any given day is calculated as:

$$ET_c = ET_o \times K_c \quad (1)$$

where K_c is a factor to convert ET_o to ET_c. The methodology to determine the K_c curve is explained in Appendix B.

Yield Threshold Depletion

Soil water-holding characteristics, effective rooting depths, and irrigation frequency are used with rainfall and ET_c data to calculate a daily water balance and determine effective rainfall and ET_{aw}, which is equal to the seasonal cumulative ET_c minus the effective rainfall. Irrigations are timed so that the estimated soil water depletion (SWD) does not exceed the yield threshold depletion (YTD), which is calculated as the product of the allowable depletion and the plant available water content within the crop rooting depth. The plant available water content is computed as the product of the soil available water-holding capacity and the effective rooting depth. The allowable depletion is a crop and soil specific factor that defines the fraction (or percentage) of the available water content within a rooting zone that can be depleted between irrigation events. For many crop and soil combinations, an allowable depletion of 50% is adequate. For drought tolerant crops with dense root systems, the allowable depletion can be increased by 10 to 15%. For drought sensitive crops, with sparse root systems, allowable depletions can be decreased byt 10 to 15%. In the off-season, the maximum soil water depletion (SWD_x) is set equal to 50% of the available water content within the top 0.3 m. It is assumed that, without a crop, the soil in the top 0.3 m cannot lose more water than SWD_x

Crop rooting depth, maximum soil depth, and water holding characteristics are used to calculate the yield threshold depletion (YTD), which is used to make a crop and soil specific irrigation schedule. The user selects one of three general categories for the soil water holding characteristics. If a light soil is selected, the program uses 0.075 mm per mm for the available water holding capacity of the soil. A value of 0.125 mm per mm is used for the available water holding capacity of a medium textured soil. For a heavy soil, a value of 0.175 mm per mm is used. The selected value is multiplied by the smaller of the rooting depth or the soil depth to determine the plant available water (PAW) within the soil reservoir at the maximum rooting depth for the crop. To simplify graphing, the water holding content at field capacity is estimated as twice the available water holding content. The YTD is calculated as the product of the allowable depletion (expressed as a fraction) and the PAW. In reality, the rooting depth and PAW increase as the roots grow, but, because of the additional complexity, this is ignored in the SIMETAW II model.

Water Balance

All input data and calculations in the SIMETAW II application are in metric units. To covert to A-ft, the depth of water (mm) is multiplied by the area of the land-use category (hectares) and the product is multiplied by a conversion factor of 0.008107.

$$\text{mm} \times \frac{1\,\text{m}}{10^3\,\text{mm}} \times \text{ha} \times \frac{10^4\,\text{m}^2}{\text{ha}} \times \frac{1\,\text{A}-\text{ft}}{1233.482\,\text{m}^3} = 0.0081071\ \text{Ac}-\text{Ft}$$

Agricultural Crops

The daily change in soil water content is calculated as D_{sw}=ET_c–E_{spg}- E_r for agricultural crops, where ET_c is the crop evapotranspiration, E_{spg} is the effective water contribution from seepage, and E_r is the effective rainfall. ET_c on every day of the year is computed as the product of ET_o and K_c value, which equals the higher of the off-season (OK_c) and in-season (IK_c) crop coefficient on the same date. The IK_c curves are determined from the weighted mean Kc values and critical dates in the crop and soil information (CSI) comma delimited data files. The OK_c values are computed as a function of the ET_o rate and soil wetting frequency, which were determined from the PRISM, NCDC, and C_F data. During the off-season, it is assumed that the K_c value on any given date cannot be lower than the OK_c value. Seepage (S_{pg}) is estimated as 0.3 inches per foot of maximum root depth per month, so $Spg = 0.025 \cdot RD_x / (days\ /\ month)$. Effective seepage ($E_{spg}$) is calculated from the S_{pg} and the soil water depletion. If the soil water depletion is greater than S_{pg}, then E_{spg} = S_{pg}. Otherwise, E_{spg} = SWD, the soil water depletion. Then the soil water depletion adjusted for seepage is calculated as SWD' = SWD – E_{spg}, which could be zero or some positive number if the ET_c is greater than the seepage.

The effective rainfall (E_r) is calculated in a similar manner as the effective seepage. If the precipitation (Pcp) is less than the SWD′, then E_r = Pcp. Otherwise, E_r = SWD′, and the daily change in soil water content is SWD = ET_c – E_{spg} – E_r = 0.

On every day of the year, the soil water depletion is calculated as SWD = SWD_p + Dsw, where SWD_p is the soil water depletion from the previous day and D_{sw} is the change in the soil water depletion on the current day. Irrigation dates and amounts are determined by comparing the SWD with the management allowable depletion.

Growers use a management allowable depletion (MAD) to help determine when and how much to irrigate. This is the amount of water that they want to deplete from the soil before irrigating, and it can depend on many crop, soil, and management factors. It is impossible for one to know how growers determine their MAD, but a main factor in determining a MAD is to estimate the yield threshold depletion (YTD), where the YTD is the soil water depletion that should not be exceeded to avoid yield reductions due to water stress. In SIMETAW II, the YTD is estimated as 50% of the plant available soil water content in the effective crop root zone. The product of the smaller of the maximum rooting depth and maximum soil depth and the available water holding capacity is used to identify the effective rooting depth for a particular crop and soil combination. Values for maximum soil and root depth are read from the crop and soil information "CSI" data files. The plant available water content is computed and multiplied by 0.50 to obtain the YTD from the end of the crop rapid growth period to the end of the season. During initial growth period of field crops, the root depth is fixed at 0.3 m, but it increases to the maximum depth at the end of the initial growth. SIMETAW II uses the YTD as the MAD except it is adjusted slightly to force the last irrigation to be applied so that the soil water content is low at the end of the season. In the program output, the column with the heading SWD_x contains the MAD data that are used for scheduling

When scheduling irrigation, if $SWD_p + D_{sw} > SWD_x$, then the net application is NA = $SWD_p + D_{sw}$. Otherwise, NA =0. On each date, the soil water depletion is calculated as SWD = $SWD_p + D_{sw}$ – NA, so the SWD returns to SWD = 0 on an irrigation date. This procedure is followed throughout the in-season period.

During the off-season, there is no irrigation and, therefore, NA = 0 on all off-season dates. However, Dsw and SWD are computed in the same manner all year. During the off-season, the soil water depletion cannot exceed 50% depletion of the soil water content within the upper 0.3 m depth of soil (i.e., the off-season SWD_x). After the last day of the season, if SWD already exceeds SWD_x, the SWD will not increase. The SWD can decrease, however, if D_{sw} is negative as the result of seepage and/or rainfall. Once the SWD is less than the off-season SWD_x, it can increase again, but it cannot exceed the off-season maximum. Commonly, in California, the winter rainfall will decrease the SWD back to zero. Thus, the SWD prior to the next season is often close to field capacity.

Because rice is grown in paddies with continuous standing water, the water balance requires a different calibration method. For the other crops, we calculate the change in soil water content as: $D_{sw} = ET_c - E_{spg} - E_r$ on each day. However, water is continuously applied, so the crop is irrigated each day. We assume that all seepage is effective, so $E_{spg} = S_{pg}$. For calculation purposes, it is assumed that the daily change in soil water content (D_{sw}) is replaced by a net application (NA) on each day of the growing season up to 20 days prior to the end of the season. Growers typically drain their fields about 20 days before the end of the season, so there are no net applications during that period. The losses to evapotranspiration during that 20-day period are assumed to come from soil water stored prior to the beginning of the season. Since rice is growing mainly in standing water, it is not possible to compute a daily SWD or to determine when to apply irrigation. Therefore, it is assumed that NA=ET_c on each day of the season. Rainfall is not included in the daily water balance calculations for rice. The annual total rice ET_{aw}, however, can be improved by adding the NA values during the season and subtracting the total seasonal precipitation. This assumes that all of the rainfall is effective and the contribution decreases the need for an equal amount of net application (NA).

Riparian Vegetation

Riparian vegetation grows near sources of surface and ground water and receives much of its water from seepage. Since riparian vegetation is believed to receive sufficient water from seepage to avoid transpiration reducing water stress, the contribution of seepage was set equal to the ET_c on each day of the year. Thus, the daily change in soil water content was calculated as $D_{sw} = ET_c - E_{spg} = 0$. Riparian vegetation is not irrigated and, therefore, there is no ET of applied water for surfaces covered with riparian vegetation. Precipitation is ignored in the riparian vegetation water balance calculations because effective rainfall cannot be calculated when the soil water content is not allowed to drop.

Open Water Surfaces

For open water surfaces, the seepage is lost rather than gained, so, unlike the other surfaces, $D_{sw}=ET_c+E_{spg}$ on each day. In this case, however, the E_{spg} is equal to the sum of the E_{spg} going to all other surfaces in the sub-area. Precipitation is ignored in the water balance calculations because effective rainfall cannot be calculated when the soil water content is not allowed to drop. Actually, all precipitation on water surfaces is effective.

Native Vegetation

Native vegetation differs from riparian vegetation in that seepage does not supply sufficient water to the plants to match ET_c and avoid transpiration reducing water stress. For native vegetation, the daily change in soil water content is calculated as $D_{sw}=ET_c–E_{spg}– E_r$, which is exactly the same procedure used for agricultural crops. The difference is that there are not applications of irrigation water so NA = 0 always. Native vegetation typically goes dormant during the summer months, which reduces the K_c value to near zero and hence ET_c is very low. The ET_c increases again in the fall after the rains begin and the soil water content increases.

Urban

Indoor domestic and industrial urban water use was not considered in the SIMETAW II program. Outside urban water use was estimated by assuming that approximately half of the urban land area is covered by vegetation and the remainder is hardscape. Because of the wide variation in urban vegetation and the lack of information on mixed vegetation evapotranspiration, the crop coefficients to estimate urban landscape evapotranspiration are at best a guess. If the urban landscape was covered by half cool-season and half warm season turfgrass, the well-watered, summertime crop coefficient would be approximately Kc=0.70. We assume that half of the surface area is hardscape, which reduces the estimated summertime crop coefficient to Kc=0.35. Because of efforts to conserve urban landscape irrigation water and the fact that many cities and towns have unirrigated vacant lots, the summertime crop coefficient was reduced slightly to Kc=0.29. During the late fall, winter, and early spring, much of the Central Valley receives rainfall and the ETo rates are lower than during the summertime, so non-summer Kc values must be higher (see Fig. B.3). Urban landscape crop coefficients are treated like a type 3 crop where the Kc=0.59 on December 31 and January 1. From 1/3 to 2/3 of the year (30 April to 1 September), the Kc=0.29. From 1January until 30 April of the year, the crop coefficient decreases from Kc=0.59 to Kc=0.29. From 1 September until 31 December, the crop coefficient value increases from Kc=0.29 to Kc=0.59. However, because of the low ETo rates and high rainfall during winter, which leads to high bare soil Kc values, the actual Kc values are higher during the fall, winter (see Appendix B). Therefore, the selection of the wintertime Kc value has little impact on the estimation of urban landscape evapotranspiration, which is mainly controlled by ETo rate and rainfall effects on the bare soil ET rate.

ET of Applied Water (ETaw)

Definition

Evapotranspiration of Applied Water (ET_{aw}) is the sum of the net irrigation applications to a crop during its growing season, where each net irrigation application (NA) is equal to the product of the gross application (GA) and an application efficiency fraction (AE), i.e., NA = GA × AE. The gross application is equivalent to the applied water, and the application efficiency is the fraction of GA that contributes to crop evapotranspiration (ET_c). The ET_o, ET_c, and K_c values for two sample years are shown in Figure 5.

For all surfaces except open water and riparian vegetation, daily water balance calculations start with the soil water content on the previous day (SWC_o). Then the water losses to ET_c are subtracted to determine the soil water content on the current day as $SWC_1=SWC_o–ET_c$. This is the soil water depletion adjusted for ET_c. Next, the effective seepage (E_{spg}) contribution to the water balance is computed by comparing the seepage (S_{pg}) with SWC_1. If $S_{pg}<SWC_1$, then $E_{spg}=S_{pg}$, otherwise, $E_{spg}=SWC_1$. Then the soil water content based on ET_c and effective seepage is calculated as $SWC_2=SWC_1+E_{spg}$. The soil water content is adjusted for effective rainfall by comparing the precipitation (P) with SWC_2. If $P < SWC_2$, then the effective rainfall is calculated as $E_r=P$. Otherwise, $E_r=SWC_2$. Then the soil water content based on ET_c, effective seepage, and effective rainfall is calculated as $SWC_3=SWC_2+E_r$. Therefore, the final estimate of soil water content without considering irrigation, is given in terms of the daily change in soil water content (D_{sw}) as $SWC_3 = SWC_o - D_{sw} = SWC_o - (ET_c - E_{spg} - E_r)$.

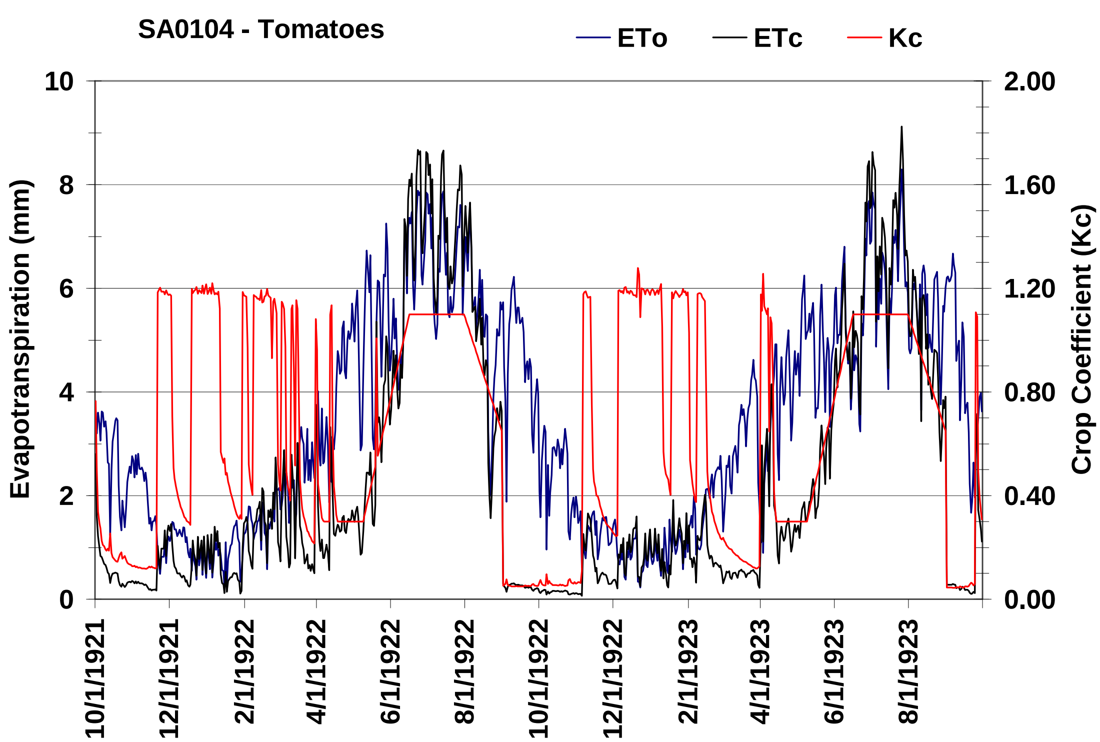

Figure 5. Crop (ET_c) and reference (ET_o) evapotranspiration and crop coefficient factors for 1921 – 1922 water years for a tomato crop grown in the Sacramento-San Joaquin Delta.

Irrigation is applied whenever the soil water content on a given day would fall below the management allowable depletion (MAD) set for that date. The net application (NA) amount is the depth of water needed to raise the soil water content (SWC_3) back to field capacity (FC) on the irrigation date. On each irrigation date, the NA is equal to SWC_3, so the actual soil water content on each day of the season is calculated as: $SWC = SWC_o - D_{sw} + NA$, where SWC_o is the soil water content on the previous day, NA is the net application, which is zero on non-irrigation days, and D_{sw} is the daily change in soil water content expressed as

$$D_{sw} = ET_c - E_{spg} - E_r$$

By definition, ET_{aw} is the amount of applied irrigation water that contributes to ET_c; therefore, ET_{aw} is the sum of the net irrigation applications during a cropping season. The ET_{aw} for *n* irrigation events is therefore calculated as: $ET_{aw} = NA_1 + NA_2 + \cdots + NA_n$. This is the method used to determine the ET_{aw} in SIMETAW II. Although not calculated in SIMETAW II, the seasonal diversion of irrigation water needed to produce a crop is calculated as:

$D = \frac{NA_1}{AE_1} + \frac{NA_2}{AE_2} + \cdots + \frac{NA_n}{AE_n}$, where NA_i and AE_i are the net applications and application efficiencies on the i^{th} irrigation date of the season. Assuming AE is the apparent, seasonal application efficiency, the seasonal irrigation water diversion can be calculated as:

$D = \frac{ET_{aw}}{AE}$, where AE is the apparent, application efficiency fraction for the season.

Water Balance Calculations

The K_c values were based on the ET_o data and crop, soil, and management specific parameters from a row in the CSI data files. During the off-season, crop coefficient values were estimated from bare soil evaporation as previously described. For effective rainfall calculations, it is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Because the water balance was calculated each day, rainfall runoff and surface water running onto a cropped field are ignored.

In the SIMETAW II program, seepage from the rivers and canals to the ground water and into the effective root zone is estimated as 0.3 inches per foot of root depth for all surfaces except rice and open water, which are assumed to be in equilibrium with the influx of seepage water.

During the off-season, the maximum depletion allowed is 50% of the PAW in the upper 30 cm of soil. It is assumed that soil evaporation is minimal once 50% of the available water is removed. If the soil water depletion (SWD) is less than this value, the ET_c is added to the previous day's SWD to estimate the current SWD. Once the SWD reaches the maximum depletion, it remains at the maximum depletion unless rainfall decreases the depletion. If rainfall occurs, the SWD depletion decreases by the rainfall amount but the SWD can never be less than zero. If the SWD at the end of a cropping season starts at some value greater than the maximum soil water depletion, the SWD is allowed to decrease with rainfall additions but it is not allowed to increase with ET_c (Fig. 7).

If a crop is pre-irrigated, then the SWD is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the SWD on the day preceding the season is determined by the water balance during the off-season before planting or leaf-out. It is assumed that the initial SWD equals zero on September 30, 1921. After that the SWD is calculated using water balance for the entire period of record.

During the growing season, the SWD is updated by adding the ET_c on the current day to the SWD on the previous day (Fig. 7). If rainfall occurs, SWD is reduced by an amount equal to the rainfall. However, the SWD is not allowed to fall to less than zero. This procedure automatically determines the effective rainfall as equal to the recorded rainfall if the amount is less than the SWD. If the recorded rainfall is more than the SWD, then the effective rainfall equals the SWD. The method ignores runoff and water running onto the field, but this is a minor problem in most irrigated fields in California. Irrigation events occur on dates when the SWD would exceed the YTD. It is assumed that the SWD returns to zero on each irrigation date. The ET_{aw} is calculated both on a seasonal and an annual basis as the cumulative ET_c minus the effective rainfall. The calculations are made for each year over the period of record as well as an overall average over years. The results are output to a summary table.

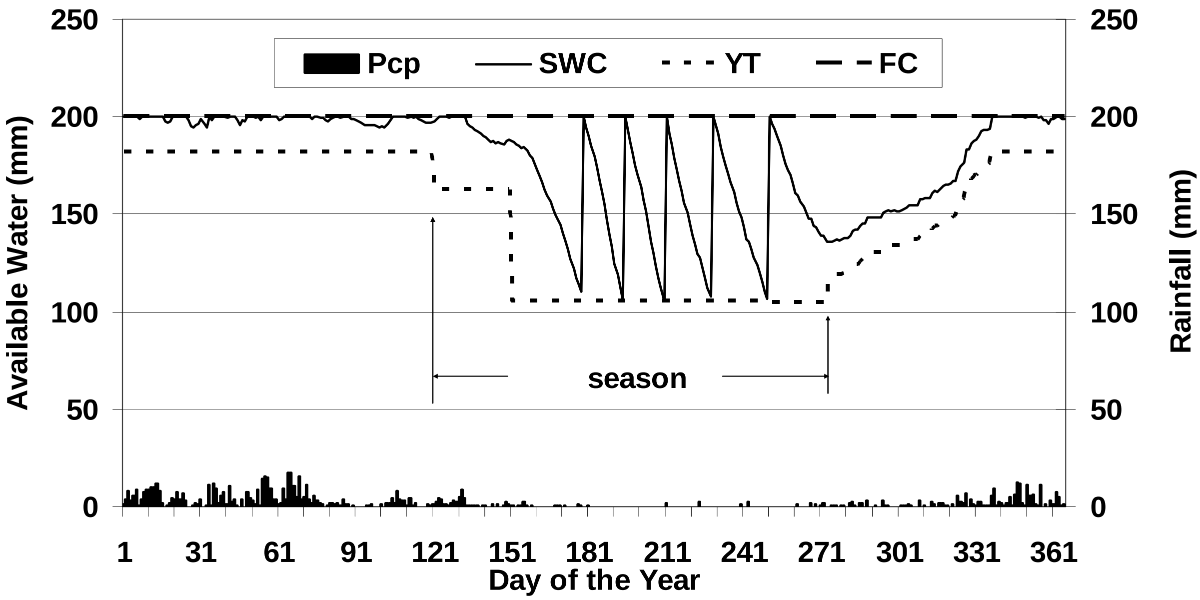

Fig. 7. An annual water balance for maize showing fluctuations in soil water content (SWC) between field capacity (FC) and the yield threshold (YT) and precipitation (Pcp).

10. SUMMARY

A daily water balance was used to estimate the volume of irrigation water needed for each of the 17 land-use categories for 46 DSAs covering the Central Valley of California. Most of the land-use categories are agricultural, but they also include urban, riparian vegetation, water surfaces, and native vegetation. Data files containing the area covered (hectares) by each of the 17 land-use categories within each DSA are used by SIMETAW II to determine year-to-year changes in volumes of ET_c and ET_{aw} based on the daily water balances.

Reference evapotranspiration (ET_o) was determined using the Hargreaves-Samani equation for estimating the evapotranspiration of 12-cm tall cool-season grass pasture (ET_{HS}) and correction factors to estimate the daily time step standardized reference evapotranspiration equation for short canopies (ASCE-EWRI, 2005). There was insufficient climate data to compute the standardized reference evapotranspiration ET_o prior to the development of CIMIS (1985), so the Hargreaves-Samani equation, which uses the latitude, elevation and maximum and minimum temperature, and climate data from the USDA PRISM program were used to estimate ET_{HS}, which in turn was used to estimate ETo using correction factors.

The USDA PRISM program provides monthly maximum and minimum temperature and precipitation data on a 4×4 km grid over California. Daily data, however, are needed to calculate a water balance on a daily basis. Therefore, nearby, long term daily NCDC climate station data were used to estimate daily maximum and minimum temperatures and precipitation from the monthly PRISM data for each 4×4 km grid. The 4×4 km grid data within each DSA were used to determine the daily maximum and minimum temperature and precipitation for each of the 46 DSAs for water years 1922-2003. The Hargreaves-Samani equation was used to calculate daily ET_{HS} for each of the grids.

Although the Hargreaves-Samani equation provides fairly accurate estimates of ET_o, it does not account for variations in wind speed and humidity, and it only partially accounts for variations in radiation. Therefore, correction factors (C_F) were developed to estimate the modified Penman-Monteith equation standardized reference evapotranspiration (ET_o). Correction factors were determined by comparing ET_o calculated from daily CIMIS data and ET_{HS} calculated using nearby NCDC climate station data. A GIS map of correction factors was developed and the C_F values were applied to convert daily ET_{HS} to ET_o for each 4×4 km grid for the period of record.

Weighted mean soil water holding capacities and maximum soil depths were determined for 4×4 km grids over the study area using individual soil characteristics from the USDA SSURGO data base. Mean DSA soil characteristics were determined using the 4×4 km grids. The results were archived by DSA in two rows of the crop and soil information ".csv" files.

The mean maximum crop rooting depths were determined by land-use category and DSA. For each land-use category and DSA combination, the fraction of the land-use category area that was occupied by each crop was determined and multiplied by the maximum rooting depth. The products were totaled to determine the weighted mean maximum rooting depth for that land-use category and DSA. These calculations were done in the "KcDSA.xls" analysis file and the results were included as a row in the crop and soil information ".csv" files.

Plant available water was determined by combination of DSA and land-use category using the soil water holding characteristics and the maximum soil or rooting depth, whichever was smaller. The plant available water was used with the ET information to determine the daily water balance over the period of record by DSA and land-use category combination.

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